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Low temperature heating system for greenhouses based on enclosed water curtain and liquid foam insulation

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ABSTRACT

A greenhouse water curtain heating system allows heating of the greenhouse by low-temperature water, which can be obtained from residual waste heat sources. The water curtain can be applied on the outside of the greenhouse roof or enclosed between two foils. But also enclosed water curtains suffer from high heat losses, which limits the integration of low temperature waste heat sources. An effective way of reducing the heat losses is to combine the water curtain system with retractable liquid foam enclosed between two foils. But until now, a systematic evaluation of the thermal performance of such system combination is still lacking. Thus, this study aims to fill in this research gap by evaluating the heat transfer characteristics of a double-foil greenhouse roof section installed with a combined water curtain and liquid foam system. Experimental tests have been conducted under a wide range of temperature scenarios in a climate chamber where the heat loss and heat gains from the water curtain is measured. The results have been compared with the data in the existing studies. This study revealed that combining the water curtain system with liquid foam, reduces the heat losses by half compared to using just the water curtain: the heat loss coefficient was reduced from 4.4 $W{\cdot}m^{-2}{\cdot}K^{-1}$ down to 2.0 $W{\cdot}m^{-2}{\cdot}K^{-1}$. The heat losses through the roof using the combined system are also lower than the heat losses from a double foil greenhouse with other heating systems. An average water curtain temperature of 5.1 °C above the inside greenhouse temperature can compensate for the heat losses through the roof at an outdoor temperature of −19 °C. Based on the study results, recommendations for market implantation of this technology are provided. This study confirms energetic benefit of combining water curtains and the liquid foam technology.

Introduction

A greenhouse external water curtain heating system involves the flow of water along the outside of the greenhouse envelope for either cooling [1,2] or heating [3,4] allowing heating of the greenhouse by low water temperatures, enabling use of residual heat or waste heat sources that can be used at none or low cost. There are also attempts with water curtains enclosed between two foils [5,6] or enclosed in the flutes of double sheet plastic [7,8].

Liquid foam insulation (soap bubbles), generated by a mixture of water and detergent can be injected between two foils in the greenhouse envelope to reduce heat losses and was originally developed in USA [9,10] followed by development in Canada [11] and the Netherlands and Norway [12]. It was recently also further developed and promoted in the USA [13].

This study proposes the simultaneous use of the water curtain and the liquid foam technologies in the greenhouse envelope enabling the combined advantage of low temperature heating and reduced heat losses. The double-foil greenhouse structure being used for liquid foam is also suitable for water curtains and the addition of detergent in the heating water improve the heat transfer from the water curtain [14]. In this study a climate chamber is used to measure the thermal performance of a greenhouse roof section with the enclosed water curtain heating system and the liquid foam insulation concept. This enables to determine the heat balance and determine the heat loss coefficients required to size such systems. A section of a sloped greenhouse roof enclosure was installed between a cold and a tempered climate chamber to evaluate the heat loss characteristics as a function of heating water temperature and “outdoor” temperature. The novelty of the study relates to the combined performance of the water curtain and the liquid foam insulation technologies. Such combination can improve the thermal performance of the greenhouse envelope.

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Nomenclature

A_F	Area of foil, [m^2]
c_p	Specific heat capacity, [$J\cdot kg^{-1}\cdot K^{-1}$]
$\dot{m}_w$	Liquid mass flow rate, [$kg\cdot s^{-1}$]
$P_{gain,F1}$	Heat loss though inner foil, [W]
$P_{loss,G}$	Heat loss though guard box, [W]
$P_{loss,C}$	Heat loss though calibration, [W]
$P_{loss,S}$	Heat loss though separation walls, [W]
$P_{loss,SF}$	Heat loss though separation walls between foils, [W]
$P_{loss,F1}$	Heat loss though inner foil, [W]
$P_{loss,F2}$	Heat loss though outer foil, [W]
P_{el}	Heat gain from electric heater, [W]
P_{foam}	Heat gain from supply of liquid foam, [W]
$\Delta T_{surface}$	Temperature difference between surfaces, [°C], [K]
$\overline{T_{a,i}}$	Average inside air temperature, [°C], [K]
$\overline{T_{a,o}}$	Average outside air temperature, [°C], [K]
$\overline{T_{s,i}}$	Average inside surface temperature, [°C], [K]
$\overline{T_{s,o}}$	Average outside surface temperature, [°C], [K]
$T_{w,in}$	Inlet water temperature, [°C], [K]
$T_{w,out}$	outlet water temperature, [°C], [K]
U_{loss}	Heat loss coefficient related to inside temperature, [$W\cdot m^{-2}\cdot K^{-1}$]
$U_{loss,w}$	Heat loss coefficient related to average water temperature, [$W\cdot m^{-2}\cdot K^{-1}$]
$U_{gain,w}$	Heat gain coefficient related to average water temperature, [$W\cdot m^{-2}\cdot K^{-1}$]
v	Air velocity, [$m\cdot s^{-1}$]

Water curtain technologies

Water curtains used to heat and cool greenhouses is not new, and similar technologies are presented under many different terms, like the "water blanket", "fluid-roof", "surface heating" and "fluid canopy system". Distribution of well water over a single glazed greenhouse for cooling purpose was demonstrated already in 1939 by Brown [1]. Minasyan et al. [3] describes experiments on glass houses heated by external water curtains in the USSR from 1945 to 1950 with a water flow rate in the range of 0.022 $l\cdot s^{-1}\cdot m^{-2}$ to 0.028 $l\cdot s^{-1}\cdot m^{-2}$. The greenhouse was heated to 15 °C at the floor level when outdoor temperature was −27 °C. The supply and return water temperature was 42 °C and 26 °C respectively. Thomas [4] presents in 1961 UK test results where external water curtains with waste heat from a nuclear power plant are used to heat the greenhouse roof and it was found that a water temperature of 21 °C could maintain a temperature in the greenhouse of just over 15 °C at an outdoor temperature of −7 °C.

Walker [15] describes experiments of heating a small greenhouse of polyethylene film (single layer) with water from a thermal power plant in Illinois in the spring of 1976. The results are presented in graphs that show the greenhouse temperature as a function of water temperature and outdoor temperature and a greenhouse temperature of at least 12°C is reached at an outdoor temperature of −15°C and a water temperature of 30 °C with a water flow rate of 0.094 $l\cdot s^{-1}\cdot m^{-2}$. It is also noted that if the heat output requirement is 0.31 $kW\cdot m^{-2}$ in a conventional greenhouse, then 5.9 $kW\cdot m^{-2}$ is used in this application with a water curtain. Based on indoor tests, the heat transfer coefficient from water to the greenhouse was measured at 10 $W\cdot m^{-2}\cdot K^{-1}$ and the loss coefficient from the water to the surroundings was measured to 40 $W\cdot m^{-2}\cdot K^{-1}$ [16]. Walker et al. [17] continuous the evaluation of an experimental greenhouse with external water curtain in Illionis and estimates the energy savings to 26 percent if the electricity to both auxiliary heater and pump is taken into account. The heat loss coefficient from the water surface at night was estimated to between 17.9 $W\cdot m^{-2}\cdot K^{-1}$ and 97.3 $W\cdot m^{-2}\cdot K^{-1}$, where the wind speed is having the greatest impact on the heat loss coefficient. The power output for pumping water was calculated to be 10.1 $W\cdot m^{-2}$ floor area. A simulation model was developed by Walker [18] to calculate the savings of a greenhouse utilizing the waste heat from Illionis power plants predicting a saving of 52.4 %, but the savings are reduced to 22.5 % if the water temperature is reduced by 5 °C. An extended simulation study is performed for different locations and provides the optimal water flow rate depending on pump costs and heating energy costs [19].

Enclosed water curtain systems based on water filled double skin polycarbonate have been evaluated in France by Chiapale et al. [7]. The south side was conditioned with a liquid that was supplied from below and flowing upwards between the double sheet of rigid plastic. The liquid was a mixture of water with $CuCl_2$, that increased absorbance of long-wave solar radiation. The liquid is stored in a tank that acts as a heat storage to be able to cool the greenhouse during the day and to heat the greenhouse at night via the same system. The tank is cooled with groundwater in case the temperature in the tank becomes too high. One conclusion is that evapotranspiration decreases for this greenhouse compared to a normal greenhouse due to the reduced solar radiation. A simulation model of a greenhouse with a selective filter fluid roof was developed by van Bavel et al [20] and the simulation results indicated reduced evapotranspiration and reduced ventilation requirements due to the selective filter. A model of the selective filter fluid roof greenhouse was also developed by Sadler and van Bavel [21] which was validated towards measurements. A similar system with demineralized water was measured in 1983 by Chiapale et al. [22], focussing on the development and validation of a simulation model. The absence of interior condensation or ice formation maximize the solar transmittance, however Meneses and Canham [8] found that the transmittance was reduced severely by condensed water if the flutes were drained. Recommended water flow rate for enclosed water curtain constructions is between 0.0056 and 0.0083 $l\cdot s^{-1}\cdot m^{-2}$ [23]. Van Bavel et al. [20] develops a simulation model for a conventional and a solar-heated greenhouse with water flow between two plastic layers according to Chiapale et al. [7] and calculates energy flows, temperature and humidity for typical days in Texas and France. Heat is supplied when the blade temperature is below 10 °C. The calculated energy savings are in the range of 20 % to 40 % and the need for forced ventilation is eliminated.

In Japan, the water curtain system is used to prevent low inside temperatures during cold nights by using well water in small greenhouses with strawberries [24]. Water is splayed on plastic film located above the strawberries and below the roof film. Problems that the water is gathered at the valley part of the foil is identified, and new water distribution systems are developed to realise higher water covering ratio. Ogura [25] reports that the development of water curtain greenhouses have been going on since 1979 in Japan and that the curtains can be movable or retractable to maximize sunlight during day. An experiment is conducted to compare the temperature in the water curtain greenhouse with a control greenhouse during a night that reach −6 °C. The wellwater temperature was around 15 °C and flow rate was in the range of 0.0015–0.0038 $l\cdot s^{-1}\cdot m^{-2}$. The air temperature in the water curtain greenhouse was kept above 8 °C, while the air temperature fell below 5 °C in the control greenhouse [25]. Iwasaki et al. [26] compare strawberry yield in a cooling water curtain greenhouse with a greenhouse with shading film (30 %) and a control greenhouse without shading device. They report 13–14 % higher strawberry yield for the water curtain greenhouse due to reduced leaf temperature. The shaded greenhouse did not reach the same yield as the control greenhouse, and leaf temperature was similar as in the control greenhouse. A more recent

study from Korea [6] makes a systematic evaluation of the relationship between inside temperature and the water flow rate, water temperature and the outdoor temperature. For example, a water flow rate of 0.0031 $l \cdot s^{-1} \cdot m^{-2}$ requires a water temperature of 13.1 °C to maintain an indoor temperature of 7 °C at an outdoor temperature of −5 °C [6]. At −9 °C outside temperature, the water temperature needs to increase to 20 °C to maintain the indoor temperature to 7 °C.

Applying water on the outside surface of greenhouses provides an advantageous temperature distribution profile in the greenhouse [23,27]. However, problems with algae growth, and clay deposits on the exterior, and excess indoor moisture levels were reported from a long term test campaign. Nikita-Martzopoulou [28] compares the performance of different types of experimental low temperature greenhouse heating systems using geothermal water at a temperature of 33–34 °C. One of the systems evaluated was heated by water distribution between double polyethylene foils and it was found that the light transmittance was degraded by the well water due to salt deposits on the foil, causing slightly reduced tomato yield compared to the other greenhouses.

The water is distributed over the roof or foil surface using perforated tubes placed on each side of the ridge [1] or spray nozzles [5]. An even distribution of water is crucial to achieve high heat transfer [14]. Loose foil that bends down cause the water to collect in the valleys [24]. The pipe-work design of water flow windows has been optimized with experimental and numerical approaches by Lyu et al. [29]. They studied how the water headers and water flow rate would affect the performances of the system. Ros and Vik [14] reports improved heat transfer for enclosed water curtain systems by reducing the surface tension of the water by adding 0.2% detergent. Measurements in a climate chamber on a segment of a double foil roof construction show that the water temperature can be reduced by about 4 °C with maintained performance while at the same time reducing the heat losses to ambient by about 10 % [14]. Firfiris et al. [5] makes a field evaluation of a double foil system (similar to the air inflated technology [30]), where ice formation is allowed between the foils. Here the water is pumped from a ground buried storage tank as previously tested by Chiapale et al. [7] but here with the focus of frost prevention at night temperatures as low as −10 °C.

Retractable liquid foam insulation

The retractable liquid foam or liquid foam-insulation concept was originally described in a Swedish patent from 1968 [31], but the technology was first developed in USA [9,10]. The first measurements indicated a heat loss reduction using liquid foam of about 47%. Water with the addition of 3 % concentrated detergent was used to generate liquid foam with a volume ratio of about 200:1. At risk of freezing, 12 % of the water was replaced with ethylene glycol. Another study on a liquid foam greenhouse reported an average energy saving of 30 % [32].

A fully automated liquid foam greenhouse was described by Cunningham [33], where previously reported problems with leakage and corrosion are said to have been remedied. The U-value for a construction with a foam thickness of 30 cm was measured to be between 1.1 $W \cdot m^{-2} \cdot K^{-1}$ and 1.7 $W \cdot m^{-2} \cdot K^{-1}$ under practical conditions. The very lowest value was measured at 0.85 $W \cdot m^{-2} \cdot K^{-1}$ with a detergent concentration of 4 % in cold, dry, clear and calm outdoor conditions [33]. Villeneuve et al. [34] measures the U-value of the greenhouse construction when using liquid foam to 2.26 $W \cdot m^{-2} \cdot K^{-1}$.

Aberkani [11,35] reports that the transmission losses during night with liquid foam compared to double plastic decreased by between 33 % and 64 %. The measurements were performed on a partially foamed greenhouse, which includes correlation for the areas not foamed- The energy savings tended to decrease at low outdoor temperatures, as the liquid foam rate of degradation increased at low temperatures. Another study [35] reported energy savings due to the liquid foam between 23 % and 31 % in Januari, 29 % to 42 % in February, 35 % to 50 % in March, 57 % to 78 % in April and 49 % to 66 % in May. Aberkani [36] investigates how shading can be performed with either water sprinkled between the foils or liquid foam finding that quality of the tomatoes can be achieved without affecting the yield. Reduced transmission losses by using foam are estimated to between 40 % and 50 %, however the total energy saving from using liquid foam was reported to 7 % for a few days in February, given that the foamed surface only corresponds to 33% of the enclosure area.

Aberkani et al. [37,38] investigated how different strategies for shading with liquid foam affect growing conditions, yield and quality of tomatoes in experimental greenhouses in Quebec City and Harrow in Canada over two summers. The results show that shading using foam at high solar radiation increases the yield and the quality of tomatoes for a summer with high solar radiation, but not for a summer with relatively little solar radiation. In reference [39], the cultivation results of tomatoes in two greenhouses are compared, both illuminated with sodium lamps 16 h a day but one of them is isolated with liquid foam at night. These winter trials showed that the heat losses for the surface insulated with liquid foam decreased by 62% without affecting tomato production for the evaluated days. The reference [40] investigates how light conditions are affected in greenhouses with double-layered plastic when using sprinklers with solar radiation exceeding 600 $W \cdot m^{-2}$ and liquid foam when the solar radiation exceeds 850 $W \cdot m^{-2}$ with the aim of reducing solar radiation. No carbon dioxide was added. The measures are estimated to improve the growing climate in the greenhouse both in winter and summer, but the reduced radiation also reduces the height of the tomato plants by about 11%.

Motivation and novelty

The use of low temperatures for heating of greenhouses is of fundamental importance in the development of energy efficient and low CO_2 emitting greenhouses. Low temperature heating systems enable the use of residual waste heat which otherwise cannot be used. Excess heat from data centers is an example of such industries with residual heat that can be utilized to heat greenhouses [41]. Low temperature heating systems will also streamline the use of geothermal heat or heat pumps.

Properly sized fan coil units have proven to cover the heating demand with a supply water temperature of about 35 to 40 °C [42–44]. However, the investment cost for such heating systems are high [45] and targeting reduced heating water temperature will increase costs even further. The water curtain heating system can easily be integrated into the typical design of liquid foam insulated greenhouses as a low-cost heating system, comprising a perforated water distribution pipe located at each side of the ridge. The liquid foam technology enables the exclusion of thermal curtains and shading devices [46].

This study proposes a combined use of water curtains and liquid foam insulation, which is not previously evaluated for greenhouses, but with a potential of being energy efficient and allowing use of low temperature water for heating purpose. The typical design of liquid foam insulated greenhouses are suitable also for the enclosed water curtain concept and the surface tension reducing agents used to produce the liquid foam, also improve the thermal performance of the water curtain [14]. The use of water curtains alone increases the heat losses [45] which may reduce the number of applicable cases. Consequently, the aim of this study is to evaluate the thermal performance of the water curtain system combined with liquid foam insulation and to provide sizing guidelines for such systems related to the heat loss and water temperature requirements.

The novelty of this paper is summarized as follows:

1. This study proposes a combined use of water curtains and liquid foam insulation. This has not been evaluated for greenhouses before.
2. Experimental tests have been conducted in a climate chamber to investigate the performances of the combined system.
3. The use of surface tension reducing agents to enhance heat transfer of the water curtain is a new application for water curtains.

Method

Steady state heat loss through the greenhouse structure was measured in a climate chamber. Fig. 1B shows how the section of the greenhouse roof (specimen) was installed between two climate chambers similar to the hot-box method that is used for determination of thermal transmittance of windows or building components [47]. A controlled electric heater behind the hot baffle supplies heating by natural convection and keeps the temperature in the test cavity (T_a, (indoor side) to 20 °C. Tests were performed with setpoint of the warm chamber at + 20 °C and the cold chamber at both 0 °C and −20 °C. Air humidity level is not controlled, nor measured inside the climate chamber since no condensation on the warm inner foil is expected."

The greenhouse roof test object (specimen) consisting of two layers of the clear (UV open) foil from F-clean [48], each with an area of 1.71 m^2. The foils are mounted in aluminum rails at a distance of 0.25 m and a slope of 25°. The structure is similar to the air-inflated plastic greenhouses [30], but with a drainpipe installed in the lower end of the section. The inner foil was flushed with liquid to create the water curtain

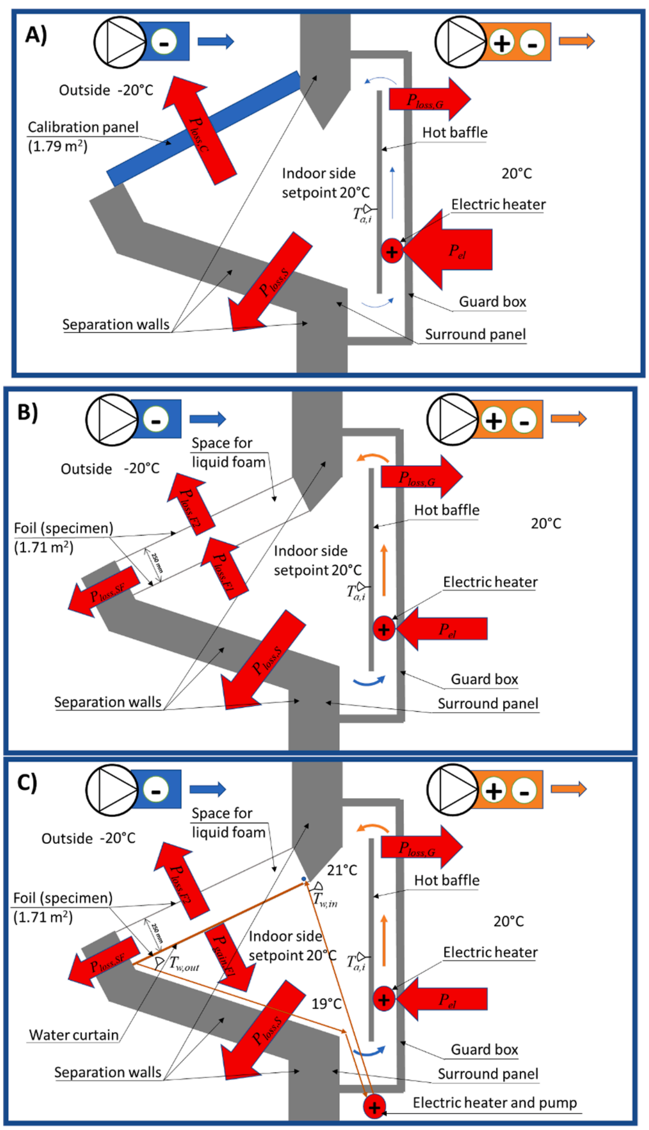

Fig. 1. Measurement setup in the climate chamber according to the hot-box method [47]. (A) shows the energy balance during the calibration setup, (B) shows the energy balance of the greenhouse roof section without water curtain and (C) shows the energy balance of the greenhouse roof section with water curtain.

system through a pipe with 0.5 mm holes distributed at a regular distance of 10 mm along the width of the foil. The liquid used for heating with the water curtain and for foam production was water with addition of 2 % dish soap. No antifreeze was used in the liquid during these tests though recommended by Groh [9] at low outdoor temperatures.

The installation of the greenhouse structure between the climate chambers requires additional walls to be installed to separate the hot side and the cold side. These additional walls were built of cellular plastic with a thickness of 0.20 m and a thermal conductivity of 0.030 $W \cdot m^{-1} \cdot K^{-1}$. The guard box separating the test cavity (indoor side) from the warm side chamber is not that well insulated, but the temperature difference is small, thus major part of the heat loss is expected to pass through the test object (specimen).

Calibration procedure

Several thermocouple temperature sensors were installed on all separation walls to be used to calculate the heat transfer assuming one-dimensional heat transfer. The inner and outer surface area of each wall was measured and Table 1 shows the average indoor-outdoor areas of all separation walls and the guard box. Surface temperature was also measured in the ceiling of the cold chamber as well as on the hot baffle, that was later used to evaluate the average surface temperature exposed to the foils in the test cavity and in the cold chamber. Several temperature sensors were also installed to measure the air temperature inside warm and cold sides of the climate chamber. In the test cavity there is only natural air circulation applied causing a temperature gradient, but on the hot and cold side chamber the air is well mixed using fan coils.

Before the greenhouse structure (specimen) was assembled a calibration panel of 100 mm cellular plastic with known heat conductivity was placed in the opening according to Fig. 1A and the climate chamber was set to an outdoor temperature of −20 °C and indoor temperature of + 20 °C respectively. When steady state was reached, data were recorded for an hour and averaged. Table 1 shows the calculated heat loss through all wall segments based on the measured surface temperature difference and the heat conductivity. The U-value of the other wall segments between the hot and cold chambers were adjusted proportionally to the "calibrated U-values" to meet the energy balance and the calibrated U-values were then applied in all other measurements.

In addition to the calibration of the climate chamber, the PT 100 four wire temperature sensors $T_{w,in}$ and $T_{w,out}$ in Fig. 1C was calibrated using a drywell. By developing correction polynomials the remaining uncertainty is estimated to be below 0.1 °C. Since the sensors were calibrated in a pair in the drywell also the maximum deviation between the two sensors was below 0.1 °C.

Measurements

Four different configurations (A to D) were measured and evaluated according to Table 2. Tests were performed for a greenhouse set point temperature of 20 °C, outdoor setpoint temperatures of 0 °C and −20 °C respectively and heating water temperatures between 20 °C and 35 °C. The liquid used in the water curtain was water with the addition of 2.0 % detergent (see Fig. 2A). No antifreeze was used in the liquid, thus for the tests at −20 °C a 15–30 min de-icing period was initiated every morning by flushing warm water and shortly raising the temperature in the cold chamber until the ice layer separates from the outer foil. The liquid foam was generated using a fan blowing through a 1 mm open cell pond filter which is sprayed with the same detergent solution as used in the water curtain. For configurations C and D (Table 2) liquid foam was filled regularly, depending on the heat loss, causing a fill interval of 1 to 1.5 h for configuration E and about 0.5 h for configuration F with heating water (see Fig. 2B and Fig. 2C). It was found that an ice layer was formed on the inside of the outer foil, which increases the thermal resistance and reduced the heat loss.

Table 1
Theoretical and calibrated U-values and heat loss distribution for the different wall segments during the calibration measurement. The electrical heating power was measured to 77.8 W.

	Area	Wall thickness	Heat conductivity	Theoretical U_{loss}	Calibrated U_{loss}	$\Delta T_{surface}$	Heat loss
	[m^2]	[m]	[$W{\cdot}m^{-1}{\cdot}K^{-1}$]	[$W{\cdot}m^{-2}{\cdot}K^{-1}$]	[$W{\cdot}m^{-2}{\cdot}K^{-1}$]	[°C]	[W]
Guard box	8.960	0.040	0.025	0.625	0.625	1.9	10.9
1 Surround panel	3.134	0.300	0.030	0.100	0.100	38.3	12.0
2 Small sloping bottom part	0.484	0.200	0.030	0.150	0.152	36.4	2.7
3 Sloping bottom part	1.936	0.200	0.030	0.150	0.152	36.2	10.7
4 Left side	1.372	0.200	0.030	0.150	0.152	36.4	7.6
5 Right side	1.372	0.200	0.030	0.150	0.152	37.0	7.7
6 Plywood-frame	0.069	0.025	0.072	2.880	2.880	36.4	7.2
Calibration panel 100 mm	1.793*	0.100	0.030	0.300	0.300	35.6	19.1
Total							77.8

* The area of the calibration panel is different from the foil since it is the average of the inside and outside area, see Fig. 1.

Table 2
Conditions of tests performed.

Configuration	A	B	C	D
Two foils	X	X	X	X
Water curtain		X		X
Liquid foam			X	X

Evaluation of measurements without water curtain

Surface temperatures are measured in many points on the separation walls and the guard box to be able to calculate the heat transfer ($P_{loss,S}$ $P_{loss,SF}$ and $P_{loss,G}$). The heat loss from the test cavity (indoor side) through the test object $P_{loss,F1}$ according to Fig. 1B by measuring the electric energy to the heating element P_{el} and correcting for the energy balance according to Eq (1), valid for conditions without the water curtain.

From the energy balance illustrated in Fig. 1B, the following equations describing the heat loss through the foils can be derived:

$$P_{loss,F1} = P_{el} - P_{loss,G} - P_{loss,S} \tag{1}$$

$$P_{loss,F2} = P_{loss,F1} + P_{foam} - P_{loss,SF} \tag{2}$$

where P_{foam} is the inherent energy supplied with the foam. By measuring the electric energy to the heating element P_{el} and measuring the temperature drop over the separation walls and Guard box the heat losses $P_{loss,S}$, $P_{loss,G}$ and $P_{loss,SF}$ can be calculated using the derived U-values from Table 1.

For the cases without the water curtain (configuration A and C in Table 2), the heat loss coefficient from the test cavity (indoor side) through the foils was presented as a U-value in $W{\cdot}m^{-2}{\cdot}K^{-1}$ calculated based on the average heat loss over the two foils and the average temperature of the air and surfaces in view of the foils in the cold and hot side of the climate chamber.

$$U_{loss} = \frac{P_{loss,F2}}{A_F\hat{A}\cdot\left(\frac{\overline{T_{a,i}}+\overline{T_{s,i}}}{2} - \frac{\overline{T_{a,o}}+\overline{T_{s,o}}}{2}\right)} \tag{3}$$

Evaluation of measurements with water curtain

When the heating water curtain is activated as illustrated in Fig. 1C, the heat extracted from the heating water may contribute to heat the indoor side and the energy balance of the indoor side can be expressed:

$$P_{gain,F1} = P_{loss,G} + P_{loss,S} - P_{el} \tag{4}$$

where positive Pgain, F1 means that the water curtain supply heat into the greenhouse. Measuring the inlet and outlet water temperatures of the water curtain (T_{win} and T_{wout}) and the water mass flow rate $\dot{m}_w$, the following energy balance for the space between the foils can be derived:

$$P_{loss,F2} = \dot{m}_w{\cdot}c_p{\cdot}\left(T_{w,in} - T_{w,out}\right) + P_{foam} - P_{gain,F1} - P_{loss,SF} \tag{5}$$

Between the foils the heat transfer is enhanced by mass transfer. Since no antifreeze agent was added, the accumulation of ice on the exterior foil will affects the heat loss during the measurement. However, deicing was initiated before start of a measurement period, to reduce the influence of a thick ice layer. The liquid mass flow rate was measured by regularly collecting the fluid in a bucket and measuring time and mass using a calibrated scale. Heat capacity of water was calculated depending on average water temperature, neglecting the influence from the detergent. The temperature and volume of liquid used for foam production was measured and the foam energy input was calculated and accounted for in the heat loss calculation.

For the configurations B and D with the water curtain, the heat loss coefficient is calculated from the water curtain to the cold side according to the average water temperature and the operative temperature estimated as the average of air and surface temperature exposed to the foil in the cold chamber.

$$U_{loss,w} = \frac{P_{loss,F2}}{A_F\bullet\left(\frac{T_{w,in}+T_{w,out}}{2} - \frac{\overline{T_{a,o}}+\overline{T_{s,o}}}{2}\right)} \tag{6}$$

The corresponding heat transfer gain coefficient is calculated.

$$U_{gain,w} = \frac{P_{gain,F1}}{A_F\bullet\left(\frac{T_{w,in}+T_{w,out}}{2} - \frac{\overline{T_{a,i}}+\overline{T_{s,i}}}{2}\right)} \tag{7}$$

Optimally, the flow rate should be adapted to the heat gains required and the intention was to adjust the flow rate to keep the water curtain supply and return temperature difference at about 5 °C. Fig. 3 shows that the heating water flow rate varied from 0.005 $kg{\cdot}s^{-1}{\cdot}m^{-2}$ to 0.011 $kg{\cdot}s^{-1}{\cdot}m^{-2}$ for the water curtain concept and between 0.001 $kg{\cdot}s^{-1}{\cdot}m^{-2}$ and 0.007 $kg{\cdot}s^{-1}{\cdot}m^{-2}$ for the water curtain and liquid foam case. Unfortunately for a few points the flow rate is too high, and the supply/return temperature drop is as low as 1.3 °C which provide unnecessarily measurement uncertainty.

Results

The thermal performance of the water curtain system with and without liquid foam insulation is evaluated based on the heat losses to ambient and the useful heat gain into the greenhouse. It is as a function of water temperature and outdoor temperature as is presented in Fig. 4. In contrast to the cases measured without the water curtain being active, only the heat losses are derived based on the indoor and outdoor temperature as in Fig. 5.

Fig. 4 shows the measured useful heat gains into the greenhouse and heat loss to the outside from the different water curtain configurations B and D as a function of the water temperature and inside temperature

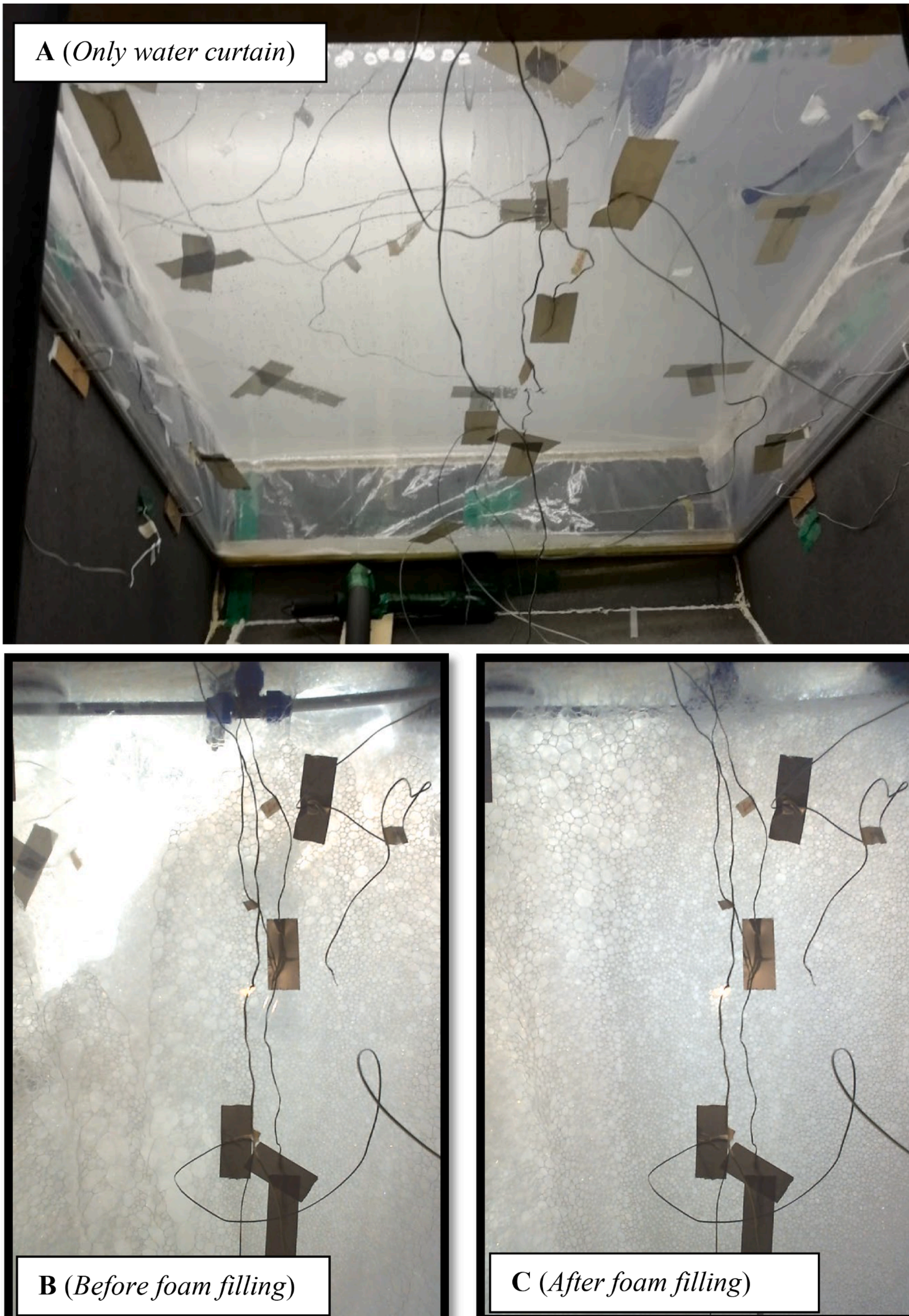

Fig. 2. (A) With detergent added, the liquid flows out evenly over the surface and become almost invisible. (B) The liquid foam levels just before filling up with more liquid foam. (C) Just after filling up with liquid foam.

(T_w-T_i). The general results are that the gains supplied into the greenhouse as useful heat is comparable low in relation to the heat losses. For the combined water curtain and foam system, increasing the water temperature with 5 °C above the balance point ($P_{gain,F1} = 0$) increase the heat losses with 35 W·m^{-2}, while the gains increase with 25 W·m^{-2}. The corresponding performance for the water curtain concept is an increased heat loss of about 40 W·m^{-2} while the gains increase with 20 W·m^{-2}. This suggests a heating system efficiency in the range of 33 % to 42 % and therefore it may not be energy efficient to increase the heating water temperature to obtain gains that can cover other heat losses from the greenhouse like ventilation losses or transmission to the ground or through walls.

Due to the heavily increased heat losses with increased heating water temperature presented in Fig. 4, it can be recommended to operate the

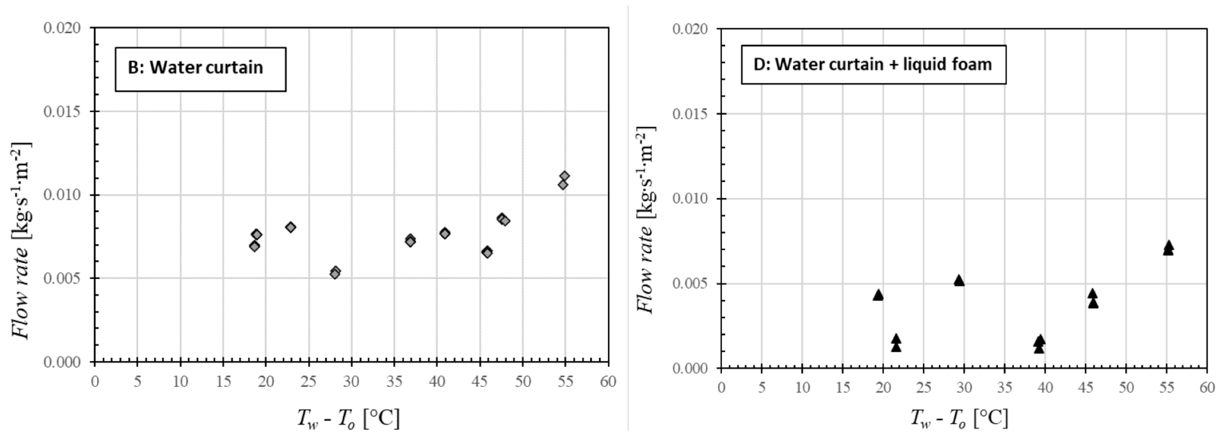

Fig. 3. Measured flow rates during the measurements.

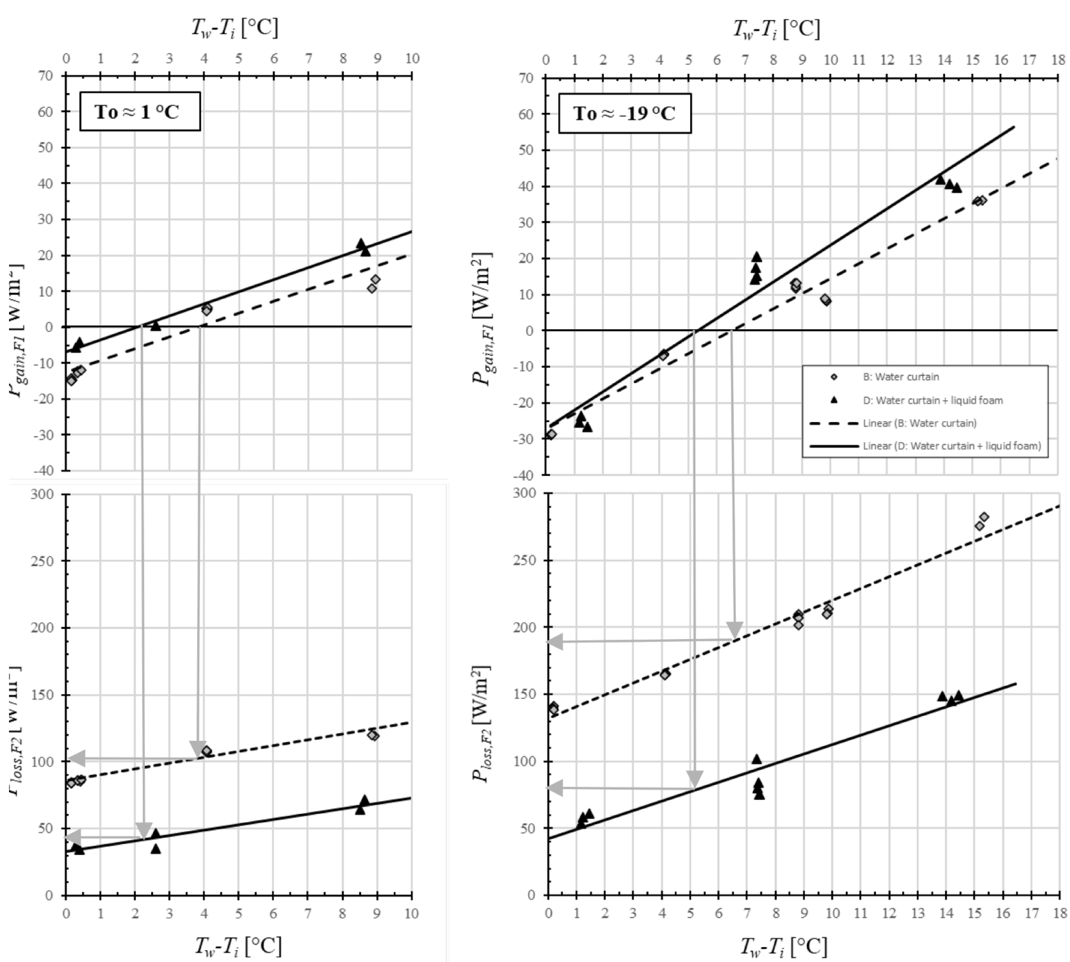

Fig. 4. Heat gains to the greenhouse and heat loss to outdoor from water curtain configurations B and D at an outdoor temperature of about 1 °C and −19 °C respectively. The inside greenhouse set temperature is 20 °C.

system at a water temperature level where the gains are zero. This means that the water curtain system only provides coverage of the heat losses through the roof and that heat losses through walls, and floor must be covered from another heating system. The required average water temperature above outdoor temperature for such operation is presented in Fig. 6. The data in Fig. 6 have been extracted from the intersection points in Fig. 4 where $P_{gain,F1} = 0$. Operating the greenhouse heating system at $P_{gain,F1} = 0$, as illustrated in Fig. 4, meaning that the water temperature can be reduced when foam is introduced providing a reduction in heat loss with foam of about 58 % when the water curtain is in operation.

Fig. 5 shows the heat loss for the configurations without the water curtain. Liquid foam reduces the heat loss by half. Comparing the heat loss with and without the water curtain at −19 °C, the heat loss increased from about 120 W/m^2 to about 190 W/m^2 without liquid foam and from 60 to 80 W/m^2 using liquid foam. However, arguing that the

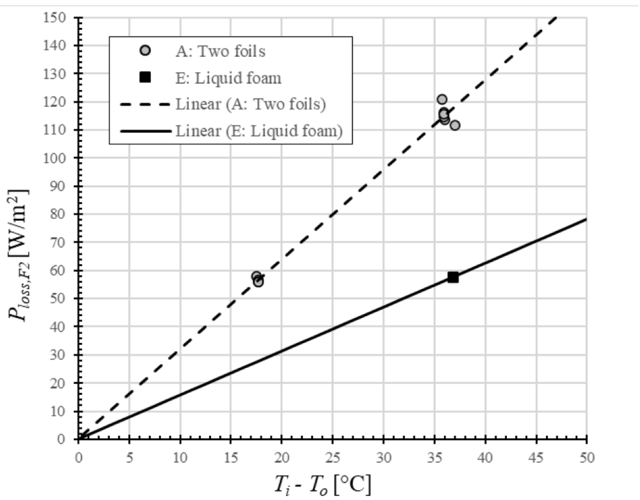

Fig. 5. Measured heat loss for the configurations related to the temperature difference between inside and outside operative temperatures.

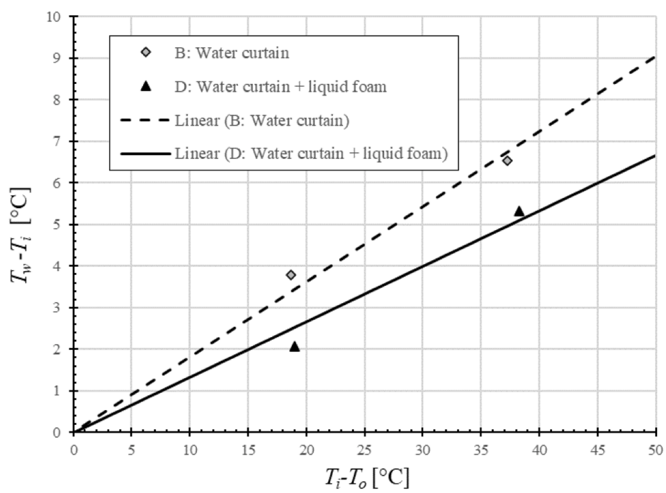

Fig. 6. Required average heating water temperature above indoor greenhouse temperature at equilibrium conditions where Pgain,F1 = 0 as a function of temperature difference between indoor and outdoor temperature difference.

enclosed water curtain concept will be implemented along with the liquid foam system it is relevant to compare the heat losses between configurations A and D. With this approach the heat losses are reduced about 30 %, from 120 W/m^2 for two foils (Fig. 5) to about 80 W/m^2 (Fig. 4) at the −19 °C case.

Heat loss coefficients (U-values) may be useful when designing greenhouse heating systems and the data presented in Fig. 7 for the water curtain configurations suggest that the U-value is fairly independent of temperature difference. The U-value is calculated based on the average water temperature and the cold side operative temperature according to Eq. (6). The fluctuations indicate some measurement uncertainty. An overview of the measured heat loss coefficients and gain heat transfer coefficients for the different configurations are presented in Table 3 as well as a comparison with data available from literature. Since the combination of liquid foam and the water curtain have not previously been evaluated there are no data in literature for that combination.

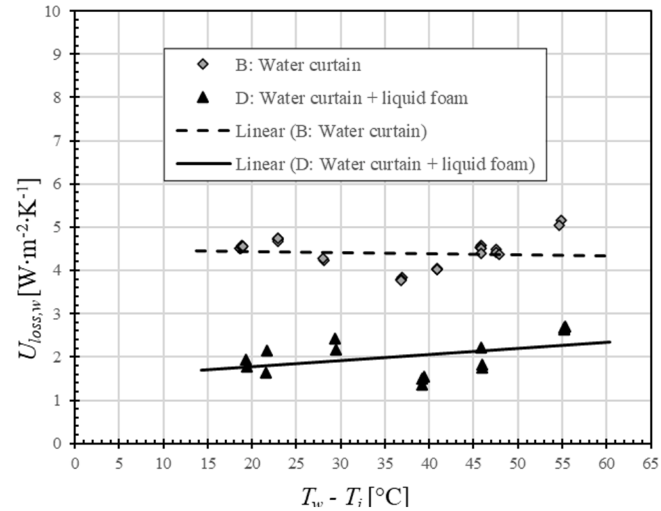

Fig. 7. Heat loss coefficient of the configurations with water curtain and water curtain + foam.

Table 3
Overview of measured average heat loss and gain heat transfer coefficients calculated according to Eq. (6) and (7) and comparison with heat loss coefficients presented by other studies.

	U_{gain} [W·m^{-2}·K^{-1}]		U_{loss} [W·m^{-2}·K^{-1}]	
	This study	Other studies	This study	Other studies
A: Two foils	–		3.2	4.0–4.5 [49,50]
B: Water curtain	1.4	Not available	4.4	6.6* [45]
C: Liquid foam	–		1.6	0.85–2.3 [33,34]
D: Water curtain + liquid foam	2.6	Not available	2.0	Not available

* Air velocity of 0.4 m·s^{-1}.

Discussion

Limitations

Due to the varying loads, in the measurements, the intension was to vary the flow rate, so that the temperature drop of the water was kept to about 5 °C, but this was not well achieved causing a quite fluctuating correlation between flow rate and outdoor temperature (Fig. 3). To reduce the influence from varying flow rate in this study, the data was calculated based on the average water temperature between inlet and outlet.

The measurement campaign investigates the influence from varying outdoor temperature and water supply temperature, but influence from water flow rate and outdoor air velocity was not evaluated in this study though Heard [45] suggest it having influence. The cooling fan located in the cold chamber cause forced convection along the outside foil which may influence the heat loss. The velocity at 5 cm above the foil surface for the + 1 °C air temperature was measured to be in average 0.4 m/s using a multidirectional air draft probe (testo 480).

The study restricts to the evaluation of thermal performance of the system without solar radiation. However, the light used in the cold chamber to be able to monitor the system through a web camera may have some radiation exchange and influence the results. The light transmission through the construction has not been evaluated during these tests. The water layer is not expected to influence the light transmittance much as previously reported [51,8], but moist or ice

accumulating on the inside of the outer foil will reduce the light transmission. Meneses and Canham [8] reported a light transmittance reduction of 1 % for water filled double-skinned polycarbonate, but after draining a reduction in solar transmission of 10 % is reported due to remaining water drops and condensation inside the flutes.

Comparison with other studies

The measured heat loss coefficient for double foils of 3.2 $W{\cdot}m^{-2}{\cdot}K^{-1}$ (Fig. 7, Table 3) is slightly lower than catalogue data which according to Bond et al. [52] is 4.0 $W{\cdot}m^{-2}{\cdot}K^{-1}$ and according to Nielsen et al. [50] is 4.5 $W{\cdot}m^{-2}{\cdot}K^{-1}$. The performed laboratory measurements do not include cold bridges in the frame nor eventual air leakage, which may be included in measured data from real greenhouse envelopes.

The measured heat loss coefficient for the 0.25 m liquid foam is about 1.6 $W{\cdot}m^{-2}{\cdot}K^{-1}$ (Fig. 7, Table 3). This is comparable with the U-value reported by Cunningham [33] for a foam thickness of 30 cm to be between 1.1 and 1.7 $W{\cdot}m^{-2}{\cdot}K^{-1}$ under practical conditions. The very lowest value was measured at 0.85 $W{\cdot}m^{-2}{\cdot}K^{-1}$ with a detergent concentration of 4 % in cold, calm and dry conditions [33]. Villeneuve et al. [34] estimates the U-value of a real greenhouse construction with liquid foam insulation to 2.26 $W{\cdot}m^{-2}{\cdot}K^{-1}$.

Though there are a few measured data on heat transfer coefficients available for external water curtains [16,17], almost none is available for enclosed water curtain systems. In a fluid canopy system evaluated by Kim et al. [6] a greenhouse temperature of about 4.5 °C is kept with an outdoor temperature of −15 °C supplying water at a temperature of 20 °C at a flow rate of 0.0033 $kg{\cdot}s^{-1}{\cdot}m^{-2}$. There are differences compared to our climate chamber measurements, which makes comparison impossible. The temperature levels are different from the climate chamber measurements and the gains from the water curtain is used to cover the additional heat loss from the greenhouse. In addition, there are no surface tension reducing agents used which is known to improve the heat transfer coefficient [14].

The only published heat transfer coefficients found for the water curtain system is for a similar “Fluid Canopy System” that was theoretically evaluated according to an equation presented by Heard et al [45]. The origin and modifications made to the equation is not clearly described. The equation provides a heat loss coefficient of 6.6 $W{\cdot}m^{-2}{\cdot}K^{-1}$ (Table 3) for the same air velocity as was measured in our conditions (0.4 $m{\cdot}s^{-1}$). No measured data for the heat transfer coefficient from water curtain to the inside of the greenhouse was found in the literature.

Recommendation for market implementation

The proposed greenhouse concept using liquid foam and enclosed water curtains demonstrates a technology that enables the utilization of low temperature residual heat for heating of greenhouses. In addition to the residual heat option, the low operation temperature of the water curtain heating system would also support the use of heat pumps for heating greenhouses improving their coefficient of performance COP. However, Fig. 4 shows that increasing the water temperature above the balance point to obtain positive gains from the water curtain, increase heat losses substantial. Due to the increased heat losses with increased water curtain temperature and the relatively low increase in gains, versus losses, the water curtain systems may not be suitable to compensate for additional heat losses through the greenhouses floor, walls and by infiltration, suggesting the system is only to compensate for the heat losses through the roof. The system may also not effectively secure the local climate around the plants and its roots. To cover additional heating demand and to secure the local climate around the plants a complementary heating system is recommended, possibly air heating or floor heating, or other low temperature heating system.

The outer foil temperature TF2 is below the freezing point when the cold chamber was kept at −20 °C. Ice formation was observed within a few days of operation and this may reduce the heat loss [5]. However, it is not clear if the ice may cause problems by blocking the draining pipe or possibly damaging the inner foil when ice sheets fall. Actions may be taken to prevent ice formation by adding antifreeze [33] or by regular de-icing using a separate warm water spray nozzle flushing between the foils. Such nozzles are already part of the liquid foam system to be able to remove remaining foam at sunrise.

An even distribution of heating water over the entire inside foil is essential to achieve the performance measured in this study. A prerequisite for good water distribution is a flat, well stretched foil that is not sagging. The used distribution pipe was not optimized in terms of hole diameter and distance between the holes. Aggravating circumstances in real applications are the risk of clogging using small holes or unevenly distributed water flow if pressure drop is too low. Contrary, the electricity demand for the circulation pump will increase with the increased pressure drop and increased flow rates. More efforts are required to optimize the flow distribution pipes, allowing stable and even distribution of water at low pump energy demands.

The closed greenhouse design used in this concept prevents roof vents supporting natural ventilation systems and cooling needs to be supplied through an active system. The water curtain system fed with cold water can supply cooling, but this requires a cold source or cooling machines operated by electricity. In addition, the water curtain will not cover the peak cooling load. Conventional fans on the gable sides are then a common solution for cooling using outdoor air but electricity is used for operation in contrast to the natural ventilation strategies.

Since the liquid foam and water curtain system provide higher inside surface temperatures it will not be possible to achieve dehumidification through condensation on the glazing, which is commonly utilized in conventional greenhouses. This means that dehumidification must be achieved using other methods like ventilation or dehumidification units with heat pumps.

In summary, the proposed liquid foam and water curtain system replace systems for heating, shading and energy conservation, but increase challenges with cooling and dehumidification. The success of the closed greenhouse structure with the liquid foam and water curtain concept is dependent on the implementation of a complete approach including low-energy technologies for cooling and dehumidification. With a completely closed greenhouse structure and water born cooling and heating systems, the carbon dioxide fertilization in greenhouses can be more effective with less CO_2 wasted into the atmosphere.

Conclusion

The present measurement campaign investigates the thermal performance of a water curtain system enclosed between two foils in the roof and how the energy performance is influenced by combining with liquid foam. The result shows that heat losses to the ambient (in Watt) increase by almost double using the water curtain (heat loss coefficient increase from 3.2 to 4.4 $W{\cdot}m^{-2}{\cdot}K^{-1}$). The heat gain coefficient from the water curtain to the inside is measured to 1.4 $W{\cdot}m^{-2}{\cdot}K^{-1}$. Increasing the water temperature will increase heat losses significantly although useful gains to the inside only increased marginally. Thus, it is recommended to use another heating system to compensate for heat losses through walls and the ground. Heat losses through the roof, will be the dominating heat loss in large greenhouses.

Combining the operation of the water curtain with liquid foam reduces the heat losses to about half of the heat losses compared to the enclosed water curtain and the heat losses are also lower than the heat losses from a regular structure with double foils with a heat loss coefficient of 3.2 $W{\cdot}m^{-2}{\cdot}K^{-1}$. Adding the liquid foam insulation to the water curtain, the heat loss coefficient is reduced from 4.4 $W{\cdot}m^{-2}{\cdot}K^{-1}$ to 2.0 $W{\cdot}m^{-2}{\cdot}K^{-1}$ and the heat gain coefficient increased from 1.4 $W{\cdot}m^{-2}{\cdot}K^{-1}$ to 2.6 $W{\cdot}m^{-2}{\cdot}K^{-1}$). The combination of water curtain and liquid foam concept enables to compensate the heat losses through the roof with low temperatures and slightly lower heat losses compared to a regular

double foil greenhouse. Using the foam insulation, an average water temperature of about 5.1 °C above the inside greenhouse temperature is enough to compensate for the heat losses from the roof at an outdoor temperature of about −19 °C.

This study confirms energetic benefit of combining water curtains and the liquid foam technology. Further studies are required to evaluate the influence on light transmission, the growing conditions and to evaluate de-icing strategies and optimize the backup systems for illumination, heating cooling and dehumidification and to evaluate the total energy balance of the concept.

CRediT authorship contribution statement

Tomas Persson: Conceptualization, Methodology, Validation, Writing – original draft. **Amélie Chaillou:** Investigation, Data curation, Formal analysis, Validation. **Pei Huang:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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